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EARTHQUAKE PREDICTION

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Introduction

Every new earthquake disaster revives the idea of earthquake prediction, the idea which was considered a few decades ago as a fantasy scientific endeavor. However, recent technical and scientific developments, as well as some social and economic pressures, have created a quite different atmosphere. Earthquake prediction has become a serious scientific activity combining the efforts and results of many disciplines, particularly those of the earth sciences. The principal purpose of earthquake prediction is to reduce the vulnerability of the population living within an earthquake prone region. For this reason, scientific disciplines other than seismology and geology are also involved; they include those dealing with various aspects of human response and environment.

During the last decade, several successful predictions were made and these sometimes stimulated unjustifiably high expectations. What is less well known is that there were also many which were unsuccessful. These helped make the expectations more realistic and provided a better understanding of the immense complexity of the whole problem.

Prediction of disastrous earthquakes is, in fact, only a part of the attempts to reduce the adverse effects of earthquakes. Many other activities fall within the terms of "prevention" and "mitigation." What can be done in the present state of the art? It is first of all evident that the processes leading to the occurrence of earthquakes cannot be stopped and it is only the introduction of technical and organizational measures which can reduce future human and material losses at the present state-of-the-art.

Seismology, at its present stage of development, can delineate regions where earthquakes are likely to occur (earthquake source regions) and estimate the probability of the occurrence of events of different sizes. There is also the possibility of calculating levels of expected vibrations at a particular site in terms of their amplitudes and frequencies or in grades of the macroseismic scale (Mercalli, MSK or others). This procedure is usually called seismic hazard assessment and provides only probabilistic estimates over longer time intervals such as 25, 50, 100 or 500 years. This assessment can also be called prediction but only in a very general sense. Seismic hazard assessment is comparable with climate assessment in meteorology. Operations of this kind produce results of only a limited accuracy, but they permit the introduction of adequate mitigation measures, e.g. seismic resistant design of buildings according to their importance, proper land use planning, regional emergency planning, etc.

Prediction complements these long term measures, by identifying within a seismoactive zone the location, time and magnitude of a single disastrous earthquake; in this case we can compare an earthquake prediction with a weather forecast.

Earthquake Prediction Methods

During the last decade, broad, multidisciplinary research programs have been conducted and a complex of methods tested in selected regions in the USA (California), the USSR (Tadjikistan, Kamchatka), China and Japan. A large number of precursory phenomena have been identified so far and applied with varying success. Precursory time for the first category of these phenomena depends on the size (magnitude) of the earthquake: the larger the magnitude, the longer the precursor time. There are also "imminent" precursors occurring a few hours before the event without any magnitude dependance. In addition to these two categories, there is a third group of precursors displaying a broad scatter of precursor times centered vaguely around a time range of several days. In principle, every "abnormal" pattern of geophysical and other phenomena is used for estimating the time, place and size of a future large event. The precursory phenomena usually considered are the following.

Variations of earthquake activity in the area

In a seismically active region, there is a certain level of activity which is known from historical macroseismic and instrumental observations. Instrumental monitoring using seismographs having been

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in operation on a global scale since the beginning of the 20th century. For a detailed study of regional earthquake activity, a dense network of seismographs is installed in the investigated area and deviations from normal (average) activity are monitored. It has been observed that large earthquakes are preceded by a "gap" in time and space, i.e. there is a drop in activity within a certain volume of the crust or upper mantle of the earth for a period of several months to several years before a large earthquake. The precursory time is proportional to the magnitude of the event. This general pattern is, however, more complicated if investigated in detail. In some cases, a swarm of small earthquakes will mark the approaching occurrence of a large event. In some regions several weeks before the catastrophic event, foreshocks are observed, i.e. the activity is increasing and the quiescence interval is reduced to a few days immediately before the event.

Catastrophic shocks are sometimes preceded by a change in the ratio between large and small earthquakes. The distribution law can be written in a simplified form as $\log N = a - bM$, where N is the number of events of a certain magnitude class M, and a and b are regional parameters. Since b equals approximately one, the number of earthquakes increases ten times if the magnitude drops by one unit. The parameter b normally decreases during time intervals preceding a catastrophic earthquake.

The location of a future strong event can sometimes be estimated when there is a sequence of shocks migrating in space along a fault. These space patterns have been observed on a number of occasions, one example being the westward migration of epicenters along the North Anatolian Fault after the destructive earthquake in 1939 near Erzerum.

Changes in water level and in water discharge of wells

Ground water levels in wells show seasonal fluctuations, however, changes superimposed over the regular trend indicate strain increase in the upper layers. In some wells the water becomes muddy. The wellhead pressure of gas producing wells shows an increase several days before an earthquake.

Surplus in radon, chemical changes in springs

Radon emanation is one of the anomalies which Soviet and Chinese experts regard as a reliable precursor. Its predictive potential was discovered first in connection with the earthquakes in Tashkent area in 1966. Radon is the natural radioactive gas present in rocks and the explanation is that layers of rock close to the surface begin to crack under stress when two blocks of lithosphere move. This process of cracking opens tiny pores and allows more radon to escape. Radon samples are usually taken from water in bore-holes 100m deep.

Ground tilting

In earthquake regions the deformations of the surface can be monitored by tiltmeters or by geodetic measurements. Standard tiltmeters are astatic pendulums or other devices very sensitive to very small inclinations of the surface. To avoid the influence of volume changes due to varying temperatures, they are installed in deep bore-holes or in galleries.

Geodetic measurements for tilting include repeated precise levellings or triangulations. Accurate surveying, made either continuously or after certain intervals, reveals irregularities in tilting but although experiments continue, the correlation with actual earthquake occurrence has never been wholly successful. A theoretical assumption has been formulated recently about the existence of a "deformation wave."

Precise triangulation, trilateration, and levelling techniques, which allow mapping of horizontal and vertical strain changes over survey lines kilometers long are now being conducted, and in some cases, routinely, to determine the strain patterns in regions where earthquakes are expected.

Velocity variations

As stresses increase in rock, microcracks originate and the process of fracturing and opening of cracks causes a decrease in seismic wave velocity. In this stage the dilatancy model seems to work because a drop in velocities has been observed for waves crossing the area of the hypocentre several months before the occurrence of a large earthquake. At a later stage, however, the increasing stress closes the cracks and the velocities return to their original value. Promising observations were made by Soviet seismologists in the Garm region where the velocity variations exceeded the estimated range of uncertainties. However, in other earthquake regions velocity variations observed before the earthquakes were usually within the error limits and this method, which seemed to be so promising, has lost some of its predictive value.

Animal behavior

Reports on unusual animal behavior before large earthquakes has been scattered over many historical reports, chronicles and other sources from the very beginning of earthquake observations. These reports were always regarded with great caution because the observations seemed to have a random, non-systematic character and appeared to be subjective. Only relatively recently, Chinese scientists included the observation of animals among the methods considered to be significant in predicting earthquake occurrences. Their systematic observations and several successful predictions demonstrated that animals are affected by the variations of some, not yet identified fields and a few controlled projects are now under way to determine what phenomena animals may sense.

Some historical reports on earthquake-related animal behavior are questionable. However, recent reports from China, Italy and Japan on abnormal behavior of cattle, dogs, rats, cats, snakes, mice, birds, fish and other species are so specific that they cannot be discredited. The precursor times for animal behavior, should it be a precursor at all, group mostly around 2-3 hours to half a day.

Laboratory experiments

There is also a variety of geographical instrumentation deployed in the investigated region such as seismographs, tiltmeters, strain meters, creep meters, gravimeters, magnetometers, resistivity monitoring equipment, water level sensors, gas emission indicators, lasers and geodimeters. In addition to these field measurements and observations additional work is conducted in laboratories.

Laboratory studies have demonstrated that certain rocks increase in volume prior to fracturing and that this dilatancy effect is due to stress-induced microcracks. This effect would increase the permeability and pore pressure, thus reducing the effective pressure at depth and accelerating the failure process or faulting in the crust. The appeal in the dilatancy-diffusion theory is that, if applicable, it should result in a number of observable variations in seismic velocities, ground level or tilt, electrical resistivity, water well levels, and gas emission. Detailed laboratory studies suggest, however, that dilatancy cannot account for the large size of many precursory signals, nor for their time history.

Another important process observed in laboratory studies is preseismic fault slip. During certain experiments designed to model the faulting process ("stick-slip" conditions) there is usually a slow propagation of creep along the fault, followed by a rapid stage of slip that becomes unstable after propagating some distance, and ending with sudden earthquake-like displacement.

National programs in earthquake prediction

Systematic investigations into prediction methodology started in large earthquake prone countries 15 to 20 years ago. The activities are concentrated in selected areas and have brought some positive results.

Japan

The Japanese program is based on the work of universities and governmental research centers and is oriented towards the prediction of an extreme event (magnitude larger than 8) in the Tokai area, southwest of Tokyo, where the earthquake potential seems to be very high. For the monitoring of precursory phenomena precise triangulation and levelling will be repeated every 5 years; several tide gauge stations have been established along the cost of the Japanese Islands; additional tiltmeters and strainmeters have been installed; the seismograph network has been substantially modernized (seismometers in boreholes, telemetry with on-line real-time observations, submarine seismometers); velocities of waves generated by explosions are evaluated; faults are mapped; changes in the geomagnetic field are monitored by proton procession magnetometers and rock samples are tested by triaxical compression in laboratories.

United States of America

The studies are centered at the San Andreas Fault in California because of the imminent earthquake threat to large cities like Los Angeles and San Francisco. A national earthquake prediction program was set up in 1973 as a part of the Earthquake Hazards Reduction Program. A very dense observation network has been established in California expanding substantially earlier networks particularly seismograph, tiltmeter and strainmeter observations. Recently, attention has been paid also to earthquake areas in the Eastern United States (New Madrid, Charleston).

The USSR

A systematic program has been under way in Central Asia and in Kamchatka and Sakhalin for two decades, and recent activities have started also in the Caucasus, the Crimea and Siberia. Observations are mainly concentrated around major cities and the work is carried out by the Republican Academies of Sciences. Soviet researchers study, in particular, precursors relating to tilting within a large area, geochemical anomalies, variations in earthquake activity and changes in seismic velocities, in addition to other "standard" methods.

China

China introduced a very ambitious program in 1966 and made the first successful prediction in 1975 when the disastrous earthquake of February 4, 1975 in the Liaoning Province was foretold. Many human lives were saved by the appropriate preparedness measures taken by the Chinese Authorities. Chinese scientists deserve also much praise for their systematic and well-founded observations of animal behavior which proved to be an important component in the family of potential precursors. In China every phenomenon which seems likely to be linked with earthquake origin is carefully studied and at present several earthquake potential areas in China are under surveillance by amateur and professional teams.

Prediction programs are in different stages of preparation in other earthquake-prone countries, e.g. in New Zealand, Turkey, Greece, and Mexico, but their size is smaller than those just described.

At the international level efforts are sponsored by the International Association of Seismology and Physics of the Earth Interior (IASPEI) and its Commission on Earthquake Hazards. Prediction work is also promoted by specialized agencies of the United Nations, particularly by UNESCO and UNDRO because of practical applications in the mitigation of earthquake effects. At present, a proposal for international test sites is under serious consideration, the main purpose being to make possible the comparison of methodologies in one region and also to permit national teams from various countries to have access to an area where new methods can be verified.

Prediction and Social Response

Concerted efforts in earthquake-prone countries have resulted in several successful predictions in China and in the USSR. These were:

SUCCESSFUL PREDICTIONS OF POTENTIALLY DESTRUCTIVE EARTHQUAKES

Place	Date	Magnitude (Richter)
China:		
Haicheng	3 February 1975	7.3
Sungpan-Pingwu	16 August 1976	7.2
	22 August 1976	6.9
	23 August 1976	7.2
Lungliu	25 May 1976	7.6
Yen Yuan	7 November 1976	6.8
USSR:		
Dushanbe	5 November 1976	5.2
N of Garm	31 January 1977	6.4
Gazli	17 May 1976 (after-shock)	6.3
Border region Iran-USSR	16 September 1978	7.7
Alaisky	1 November 1978	6.6
Dushanbe	16 April and others in 1981	4.3

There were, however, more numerous failures when, for reasons yet unknown, the precursory phenomena were either too indefinite and weak or they were simply not followed by an earthquake within the expected time interval. This experience only demonstrated the complexity of the earthquake mechanism, which is still far from being fully understood. Consequently, the uncertainty in prediction calls for special legal and organizational arrangements. Before issuing a warning, various social and economic consequences have to be taken into account. In October 1982, UNDRO and UNESCO organized in Geneva a Seminar on Earthquake Prediction Case Histories to draw conclusions from the experience gained through the predictions already made. It was evident that each country needs an official procedure to deal with warnings provided by a scientific evaluation of a team of specialists. Mechanisms of this kind are already in existence in Japan (Earthquake Assessment Committee → Chairman → Prime Minister), USA (National Earthquake Prediction Evaluation Council → Director US Geological Survey → Government, in California NEPEC → Director Geological Survey → Governor), USSR (Research Institute of the Academy of Sciences of a Republic → President of the Academy → Government of the Republic), China (Seismological Bureau of the Province → Director SB → Provincial Government, SB → State Seismological Bureau → Director SSB → State Council).

The Seminar in Geneva concluded that there were two different viewpoints from which to consider response to predictions; namely that of authorities and institutions, and that of the public. There is a need to take any prediction (scientific or non-scientific) seriously as soon as it begins to attract significant public attention, or seems likely to do so. National or local government officials should watch out for such predictions and arrange promptly for an authoritative scientific review. Any preparedness planning which follows should be matched to the capacity of the majority of the population to respond to such plans.

All warning statements should include an explanation of the basis for issuing the warning as well as a statement on the reliability of the prediction. Part of any official warning should include specific recommendations for action by individuals or families. These actions must be appropriate for, and within the capability of, the majority of the population.

In several case histories to date, it has been noted that the media sometimes tend to sensationalize or misrepresent some of the components of an earthquake prediction. As soon as practical after the formulation of an earthquake prediction, government and scientific authorities should meet with media representatives in order to establish procedures for accurate reporting of the situation as it develops.

It follows from existing case histories that without widespread public education about earthquake prediction, social disruption can ensue. It is therefore recommended that governments should develop public information programs explaining in lay terms what a prediction and warning means, how a prediction will be validated, how the public will be informed of its development, and what appropriate response they can take.

Conclusion

In conclusion it must be stated that earthquake prediction methodology is in an early stage of development. Nonetheless, studies continue in many countries and promising results are being reported from test areas where earthquake generating processes are monitored. It does not, however, seem likely that a global earthquake monitoring system similar to that of weather forecasting will be put into operation in the foreseeable future. Investigations will continue to concentrate on selected regions where large populations are exposed to earthquake risks.

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